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Dawn or dusk? Flavour physics in the hadron collider era

GUY WILKINSON

*University of Oxford,
Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK*

A review is made of the status of, and prospects for, flavour physics studies at hadron colliders in the ‘post e^+e^- era’. It is argued that exciting times lie ahead.

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1 Onset of the Dark Ages

In the heavy-flavour community at present, it is not uncommon to detect sentiments similar to those expressed by Petrarch in the early fourteenth century:

“My fate is to live among varied and confusing storms. But for you perhaps, if as I hope and wish you will live long after me, there will follow a better age. This sleep of forgetfulness will not last for ever. When the darkness has been dispersed, our descendants can come again in the former pure radiance.”

Here the writer bemoans the end of the classical age and his despair at living in a time of ignorance and low civilisation – the so-called Dark Ages. Many attendees at this workshop will know how he felt, for it is the first CKM meeting of the post- B factory era, with neither BABAR or Belle any longer taking data. In the Dark Ages, the pursuit of new knowledge ceased. Instead lone scholars in remote monasteries worked tirelessly on recording all that was known, so that existing learning would not be lost to future generations. So it is now, where efforts are underway to produce documents such as the ‘ B -factory Legacy Book’ [1]. Of course, after the Dark Ages came the Renaissance, and so physicists are comforted with the knowledge that the resumption of the classical ways (‘former pure radiance’) will arrive in due course – and indeed the e^+e^- programme will be reborn with the Super- B and Belle II projects.

A further unpleasant feature of the Dark Ages was the threat from barbarian hordes: brutish, uncivilised and terrible new forces which roamed unchecked. It is maybe unfair to accuse members of the flavour-community of regarding the LHC in such terms, but the ‘brute force’ approach of direct observation is certainly different to that which was employed at the B -factories. Of course, with LHCb, the new machine has a dedicated flavour-physics experiment; furthermore, ATLAS and CMS themselves have goals in the flavour sector. Nevertheless, doubt is sometimes expressed that the harsh hadronic environment will allow for measurements to be performed that are of the same quality and interest of those that are possible at e^+e^- machines.

An alternative view, notwithstanding the remarkable achievements of BABAR and Belle, is that flavour physics is now embarked on a new golden age. It should be recalled that historically hadron colliders have made important contributions to this discipline, for example with the observation of B -mixing [2]. The dawn of the present era of enlightenment can be dated to the Tevatron’s observation of B_s^0 oscillations in 2006 [3], and since then CDF and D0 have produced many flavour results of outstanding interest, with a very large amount of data still to be analysed. The successful start-up to the LHC gives hope that this programme will continue at CERN. Indeed – as will be argued in this report – it is not unlikely that flavour physics will provide the headline measurements of the 2010-12 LHC run.

2 Machine status and near-term prospects

The ongoing Tevatron ‘Run II’ will continue until the end of 2011. Extrapolations of the performance achieved until now suggest that around 12 fb^{-1} per experiment in total could be delivered on this timescale. Such a sample would constitute two to three times more data than have been used in analyses presented until now, and would result in a corresponding improvement in sensitivity for many interesting flavour-physics topics (not to mention the Higgs search, which is clearly beyond the remit of this review).

At the time of the workshop the LHC had delivered around $3 - 4 \text{ pb}^{-1}$ of data per experiment at $\sqrt{s} = 7 \text{ TeV}$ *, with a start of fill luminosity of $\sim 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. In the weeks that followed the number of colliding bunches was gradually increased, with the result that the luminosity was eventually boosted to a few $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. The total integrated luminosity delivered in proton collisions was $\sim 40 \text{ pb}^{-1}$ per experiment, most of which was accumulated in a two week period at the end of the run.

The special running conditions of the 2010 run compared with those that are foreseen in future both brought opportunities for the experiments, and presented challenges. The enormous change in instantaneous luminosity from the start to the end of the run meant that the trigger strategies had to evolve continuously, but thresholds could be placed at rather low values early on, with a consequent benefit in efficiency. In terms of emittance and bunch charge, values close to design specifications were quickly reached. This meant that the ‘pile-up’ per bunch crossing soon became significant. In contrast to the General Purpose Detectors (GPDs), LHCb is designed to take data in a low pile-up environment, and run at a luminosity of a few $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. This luminosity was reached during 2010, but with around 2.5 interactions per crossing in contrast to the LHCb design value of 0.4. Operating in these conditions placed a strain both on the trigger, and – with the larger than foreseen event sizes – on the offline computing.

In the 2011-12 LHC run the luminosity at the GPD interaction points will be increased, while LHCb will continue to take data in the $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ regime, but at this fixed luminosity the pile-up rate will diminish, as the number of bunches in the machine is increased. It is not possible to make reliable predictions for the amount of data that will be accumulated, but estimates of $\sim 1 - 2 \text{ fb}^{-1}$ for LHCb, and several times more for ATLAS and CMS, are not unreasonable.

Most of the numerical results available at the workshop were obtained from the $\sim 10 \text{ nb}^{-1}$ of integrated luminosity that had been analysed for the summer conferences, although plots were available for samples of $0.1 - 1 \text{ pb}^{-1}$ of data. Where possible the plots and results included in this write-up have been updated to larger datasets.

*ALICE recorded much less data, as it is designed to operate at a much lower instantaneous luminosity than the other three experiments.

3 Early heavy flavour results from the LHC

A natural early topic of study with LHC data is quarkonia. The production mechanism of J/ψ mesons and heavier states is not well understood at hadron colliders [4]. It is natural therefore to begin to study this topic at the LHC. In the $c\bar{c}$ system the data from the 2010 LHC run will allow for the measurement of inclusive prompt (i.e. not from B decay) J/ψ production cross-sections, polarisation studies, and measurements of $\psi(2S)$ and χ_c production. Taken together, these results should be able to discriminate between a range of production models. Already available at the time of the workshop, and in several cases updated since, are measurements from each collaboration on inclusive production [5, 6, 7, 8, 9, 10]. A further attraction of isolating a J/ψ sample is that decays displaced from the primary interaction vertex are a convenient signature of b -hadron production. Therefore these data have been used both to measure the inclusive differential J/ψ cross-section, and to calculate the fraction of J/ψ mesons arising from b -hadron decays. The results presented at the ICHEP 2010 conference are plotted in Fig. 1, as a function of transverse momentum of the J/ψ [11]. The shape of the differential cross-section is very similar for each experiment, despite different acceptances in rapidity. The fraction of J/ψ events from b -hadron decays agrees well between all LHC experiments, and the Tevatron.

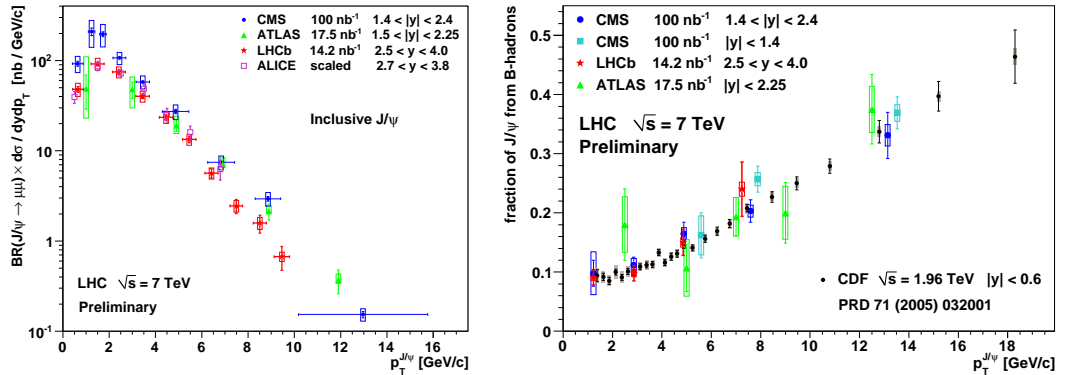


Figure 1: LHC J/ψ results from ICHEP 2010. Left: $BR(J/\psi \rightarrow \mu\mu) \times d\sigma/dydp_T$ vs. $p_T^{J/\psi}$. Right: fraction of J/ψ from B -hadrons vs. $p_T^{J/\psi}$, also showing the CDF results [11].

The onia programme of the LHC experiments has been extended to studies of the $b\bar{b}$ system. In Fig. 2 are shown the Υ family of resonances from ATLAS, CMS and LHCb as reconstructed in the $\mu^+\mu^-$ final state. These plots provide a good benchmark to assess the relative mass-resolution performances of the three experiments. CMS has also used these data to perform cross-section measurements [13].

First measurements have been made of the production cross-section of b -flavoured

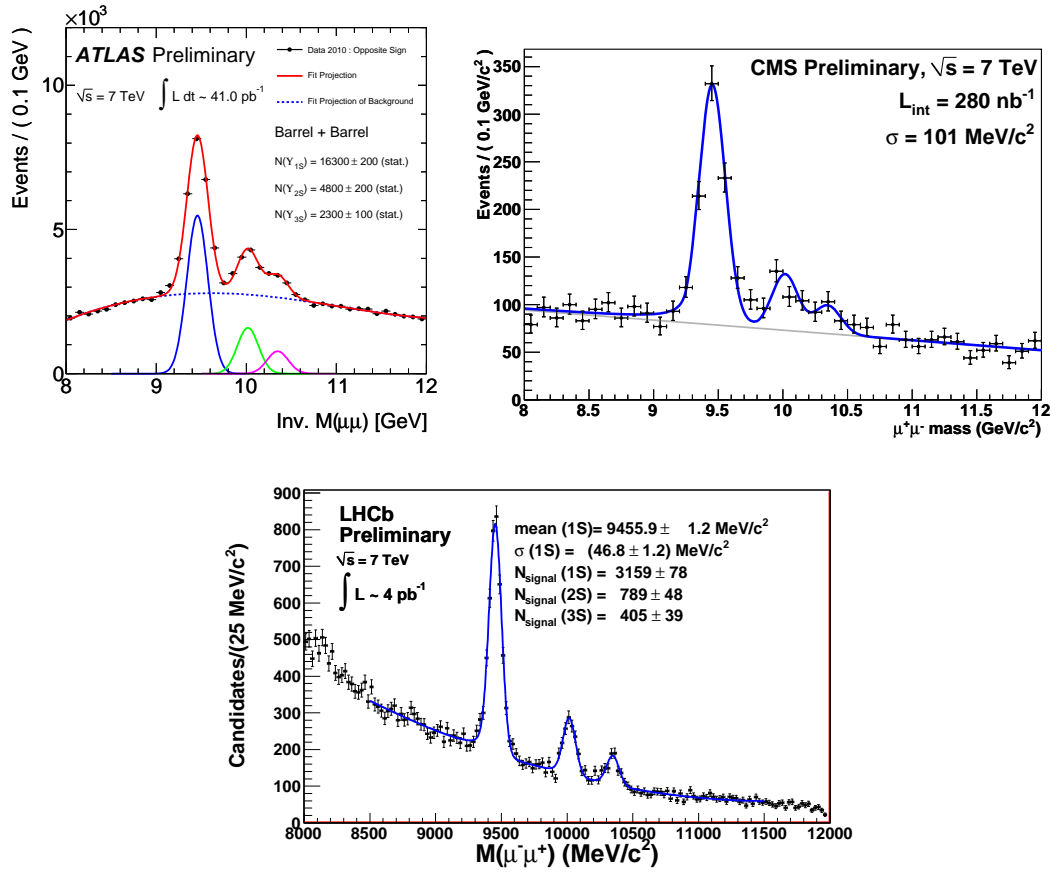


Figure 2: The Υ family of resonances as reconstructed in the $\mu^+\mu^-$ final state. Top left: ATLAS (41 pb^{-1}); top right: CMS (280 nb^{-1}) [12]; bottom: LHCb ($\sim 4\text{ pb}^{-1}$).

hadrons at the LHC. An early publication by LHCb employed the signature of D^0 -mesons displaced from the primary vertex along with a muon with the correct sign correlation for both to arise from semileptonic b -hadron decays [14]. More recently, CMS has studied the production of B^+ mesons through the decay $B^+ \rightarrow J/\psi K^+$ [15], and also inclusive b -hadron production through the identification of muons with significant transverse momentum with respect to the closest lying jet [16]. The LHCb measurements are in good agreement with the theory predictions with which they are compared (see Fig. 3 left), whereas the CMS measurements agree in shape with the predictions, but with a normalisation approximately 1.5 times larger than the MC@NLO expectation [17] (see Fig. 3 right). These results confirm that the assumptions used for the $b\bar{b}$ cross-section in LHC flavour-physics sensitivity studies, for example [18], were not overestimates.

The LHCb semi-leptonic analysis is being extended to look for D^0 , D^+ , D_s^+ and Λ_c decays in conjunction with a lepton. When cross-feed is accounted for, it then

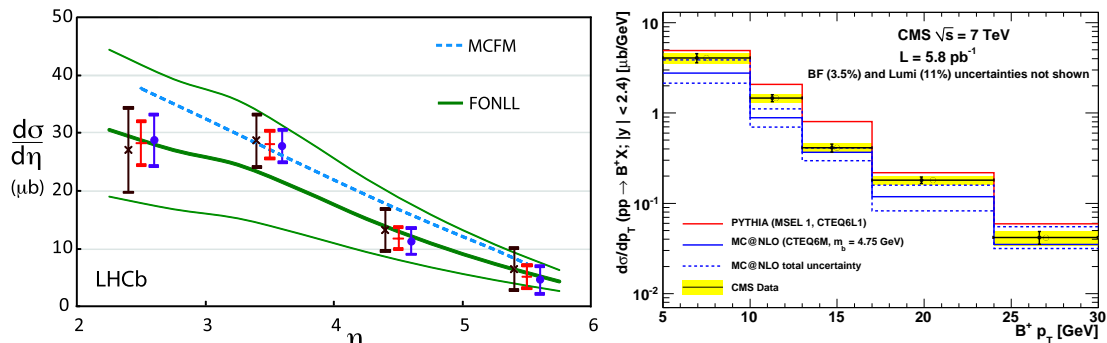


Figure 3: Left: LHCb measured production cross-section at $\sqrt{s} = 7$ TeV as a function of pseudo-rapidity averaged over b -flavoured and \bar{b} -flavoured hadrons (the middle point shown in each bin is the average of the other two points, which come from separate trigger samples) [14]. Right: CMS measured differential cross-section at $\sqrt{s} = 7$ TeV for B^+ production, with respect to transverse momentum [15]. Details on the theory predictions can be found in the references.

becomes possible to calculate the relative contribution of each b -hadron species. A preliminary result has been determined for $f_s/(f_u + f_d)$, the fraction of B_s^0 to the sum of B^0 and B^+ hadrons at the LHC at $\sqrt{s} = 7$ TeV in the forward region [19]: $f_s/(f_u + f_d) = 0.130 \pm 0.004$ (stat) ± 0.013 (syst.).

Another interesting topic of study in heavy flavour production is that of the correlation between the kinematical properties of the b - and \bar{b} -hadrons. CMS has made the first analysis of the angular correlations between b - and \bar{b} -hadrons at the LHC using a secondary vertex reconstruction method [20]. It is found that a sizable fraction of the beauty hadron pairs are produced with small opening angles.

LHCb has also performed a preliminary measurement of the cross-section of D^0 , D^+ and D_s^+ production within its acceptance [21]. It is found that at $\sqrt{s} = 7$ TeV $c\bar{c}$ production is around twenty times more abundant than that of $b\bar{b}$ events. Again these results are found to be in good agreement with QCD expectation.

4 Expectations over the coming one-to-two years

In the following few pages some examples are given of topics where interesting new results and updates are soon to be expected. This list is selective and many important analyses (for example the forward-backward asymmetry in $B^0 \rightarrow K^* \mu^+ \mu^-$ decays) are not discussed.

4.1 $B_s^0 \rightarrow \mu^+ \mu^-$

The channel $B_s^0 \rightarrow \mu^+ \mu^-$ is the b -physics rare decay *par excellence*. In the Standard Model (SM) the predicted branching fraction for this mode, at $(3.35 \pm 0.32) \times 10^{-9}$ [23], is both exceedingly low, and precisely determined. In many New Physics (NP) models, however, significant enhancements are possible. In particular, in the CMSSM at large $\tan \beta$, the branching fraction goes as $\tan^6 \beta$, meaning that searches for this mode have great discovery potential; conversely, knowing that the branching ratio of the decay lies below a certain value can impose severe constraints on NP parameter space [24].

The present 90% C.L. upper limits on this decay are 36×10^{-9} from CDF with 3.7 fb^{-1} of data [25], and 42×10^{-9} from D0 with 6.1 fb^{-1} of data [26]. Updates with the full Run II dataset will allow for improved sensitivity [27], but it is at the LHC where there are the highest hopes of observing this decay [28].

The $B_s^0 \rightarrow \mu^+ \mu^-$ search is well suited to both ATLAS and CMS [29], on account of a decay signature that allows for a high trigger efficiency, and can be pursued even when the accelerator is operating at a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. LHCb also has very good prospects. When performing this search, the sample is typically dominated after pre-selection by events containing two genuine muons, though not arising from the same decay vertex. For this reason topological information concerning the quality and isolation of the decay vertex, and the kinematics of the candidate is critical. LHCb will be able to make use of a clean sample of $B^0, B_s^0 \rightarrow h^+ h'^-$ ($h, h' = \pi, K$) events on which to calibrate the topological and kinematical variables that are used in the discrimination of signal from background. Shown in Fig. 4 is the expected performance of LHCb as a function of integrated luminosity, in terms of exclusion and observation. These curves are determined from Monte Carlo studies, but assume the measured $b\bar{b}$ cross-section at $\sqrt{s} = 7 \text{ TeV}$. Studies with early data indicate that the Monte Carlo predictions are realistic. With the $\sim 1 \text{ fb}^{-1}$ of data expected in 2011 the 90% exclusion limit should drop below 10^{-8} , or indeed evidence of a non-SM signal may emerge. A five sigma observation of the signal at the branching ratio predicted in the SM will be possible, but will require several years of operation.

4.2 CP violation in the $B_s^0 - \bar{B}_s^0$ system

Mixing-induced CP violation has not yet been observed in the $B_s^0 - \bar{B}_s^0$ system. This is because it is predicted to be small in the SM, and also because only recently has the Tevatron acquired the necessary statistics to embark on a meaningful measurement programme. (Although Belle took B_s^0 data at the $\Upsilon(5S)$, the boost was inadequate to resolve the very rapid oscillations.)

The preferred channel for studying CP-violation in the interference between B_s^0 mixing and decay is $B^0 \rightarrow J/\psi \phi$. In the SM the predicted value of the phase, $2\beta_s$, probed by this decay is very small and tightly constrained: $2\beta_s = -0.0366 \pm$

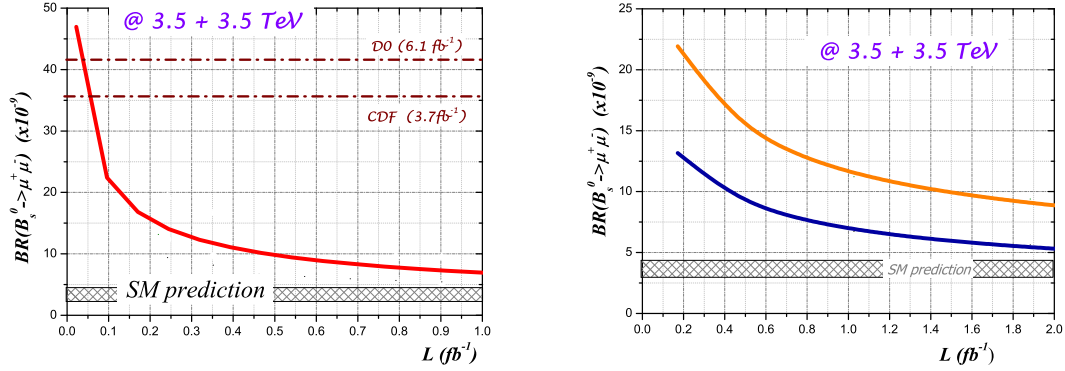


Figure 4: LHCb expected performance in the search for $B_s^0 \rightarrow \mu^+ \mu^-$ as a function of integrated luminosity at $\sqrt{s} = 7$ TeV. Left: 90% exclusion. Right: discovery, with the upper and lower curves representing 5 and 3 σ respectively.

0.0014 [22]. The most recent preliminary results available from CDF [30, 31] and D0 [32, 33], performed with 6.1 fb^{-1} and 5.2 fb^{-1} of data respectively, have a precision which is an order of magnitude too poor to be sensitive to CP-violation at the SM level. Nevertheless, NP enhancements could generate a much larger value, and indeed both measurements give weak hints, at the one sigma level, of such a possibility.

Whether there is NP affecting β_s at such an enhanced level should soon be clear at the LHC. LHCb, in particular, is well suited to this measurement [34]; simulation studies indicate that if the true phase is at the value suggested by the Tevatron results then five sigma observation will be possible with 0.1-0.2 fb^{-1} of data. The first steps on the road to performing this measurement have already been taken in 2010, with a clean sample of $B_s^0 \rightarrow J/\psi \phi$ events accumulated (see Fig. 5, left), and a proper time resolution that is found to be ~ 50 fs, which is already close to Monte Carlo expectations. Furthermore, other decay modes are now under consideration to augment the β_s sensitivity. In particular, the decay $B_s^0 \rightarrow J/\psi f_0(980)$ is a very attractive possibility, being a CP-eigenstate which therefore does not require an angular analysis, in contrast to the case of $B_s^0 \rightarrow J/\psi \phi$. This decay has been observed for the first time in the 2010 LHC run (see Fig. 5, right) [35] with a rate that indeed makes it useful for the β_s measurement.

Another interesting quantity that exists in the $B_s^0 - \overline{B}_s^0$ system is the flavour-specific asymmetry, which may be measured in semi-leptonic decays, and which is sensitive to CP-violation in $B_s^0 - \overline{B}_s^0$ mixing. D0 has recently released a result [33, 36], based on 6.1 fb^{-1} , for an observable which is effectively the sum of the flavour asymmetries in B^0 and B_s^0 mesons. Very intriguingly the measurement yields an asymmetry of order 1%, which though small is still two orders of magnitude, and 3 measurement

sigma, bigger than the tiny effect expected in the SM. Updates are awaited with great interest, both from the Tevatron and the LHC. In this measurement systematic control is crucial – percent level biases can easily enter from background asymmetries and detector effects. The LHC has the additional challenge of combating production asymmetries which are in general non-zero on account of the pp initial state.

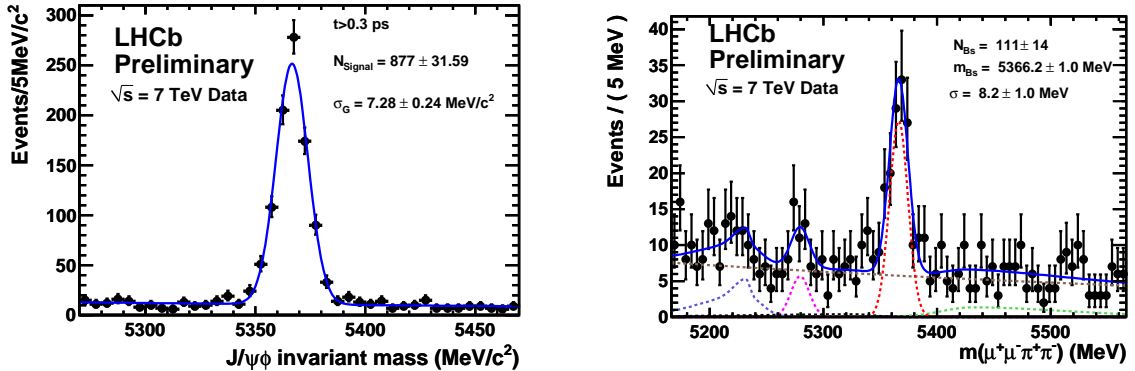


Figure 5: Left: LHCb $B_s^0 \rightarrow J/\psi\phi$ with 34 pb^{-1} . Right: LHCb first observation of $B_s^0 \rightarrow J/\psi f_0(980)$ performed with 33 pb^{-1} [35].

4.3 Hadronic b -decays

The studies considered so far all involve channels with two leptons in the final state. This characteristic provides a very distinctive trigger signature which can be exploited by any general purpose detector at a hadron collider. Attaining good efficiency on heavy mesons decays into hadronic final states, on the other hand, requires a more specialised trigger strategy. The track trigger of CDF and the high- p_T hadron trigger of LHCb are two examples of trigger systems which can perform this task.

Perhaps the most important physics goal in hadronic b -decays is the determination of the unitarity triangle angle γ . Provided that the trigger of the experiment has sufficient efficiency for the decays of interest, this measurement is very suited to hadron colliders. Firstly, the sample sizes that could be collected at the B -factories were inadequate to allow for a measurement with a precision better than 10° . The statistics that will be collected at LHCb, in particular, will be much larger. Secondly, the very powerful suite of measurements of the sort $B^\pm \rightarrow DK^\pm$ do not require a time-dependent analysis and have no need of flavour-tagging. (Flavour tagging is a priori more powerful at the $\Upsilon(4S)$ than at a hadron collider because of the quantum-correlations between the produced B -mesons.) Finally, experiments at hadron colliders have the attractive possibility of exploiting strategies involving B_s^0 mesons, such as the time-dependent study of the decay $B_s^0 \rightarrow D_s K$.

CDF has already demonstrated its capabilities in $B \rightarrow DK$ studies, by performing a first ‘GLW’ [37] $B^\pm \rightarrow D(KK, \pi\pi)h^\pm$ ($h = \pi, K$) analysis [38] with around 1 fb^{-1} of data. At this conference an ‘ADS’ [39] $B^\pm \rightarrow D(K\pi)h^\pm$ ($h = \pi, K$) study, based on 5 fb^{-1} , was presented for the first time [40] (see Fig. 6). These analyses cannot be used in isolation to extract γ , but they provide useful input to the global picture and make clear the potential of hadronic experiments in this field.

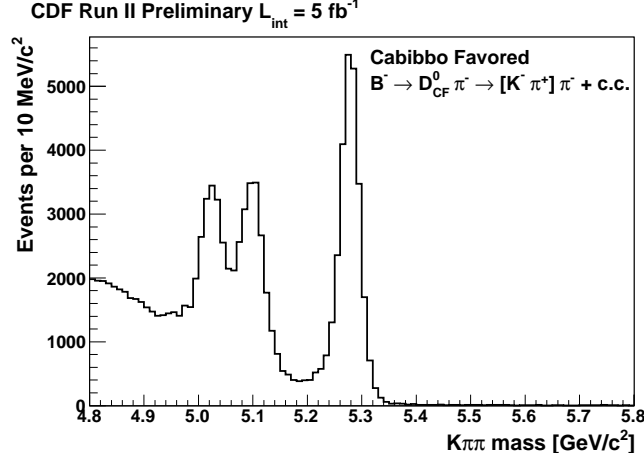


Figure 6: CDF Cabibbo favoured $B^- \rightarrow D^0(K\pi)\pi^-$ events collected with 5 fb^{-1} [40].

LHCb has already accumulated significant and clean samples in $B \rightarrow Dh$ ($h = \pi, K$) decays. As well as benefiting from its efficient trigger for hadronic decays, LHCb also profits from using its Ring Imaging Cherenkov Counter (RICH) system to distinguish between pions and kaons. This is illustrated in Fig. 7, where the RICH is used to distinguish between $B \rightarrow D\pi$ and $B \rightarrow DK$ decays. Already with a 1 fb^{-1} dataset it should prove possible to improve on many of the measurements performed at the B -factories [41].

4.4 Charm physics

The observation of charm mixing has been one of the most interesting discoveries in particle physics in recent years. Although the B -factories took centre stage in this discovery, it must be remembered that CDF played its part, with a high sensitivity study of ‘wrong sign’ $D^0 \rightarrow K\pi$ decays [42]. The priority is now to improve the sensitivity of such measurements, and those of the time-integrated and time-independent studies, to search for CP-violation in the charm system. It is clear that over the coming few years the precision of these measurements will improve greatly, given the enormous statistics still to be exploited at the Tevatron, and foreseen at LHCb [43]. Indeed, one month after the end of the workshop, the preliminary result of a 6 fb^{-1}

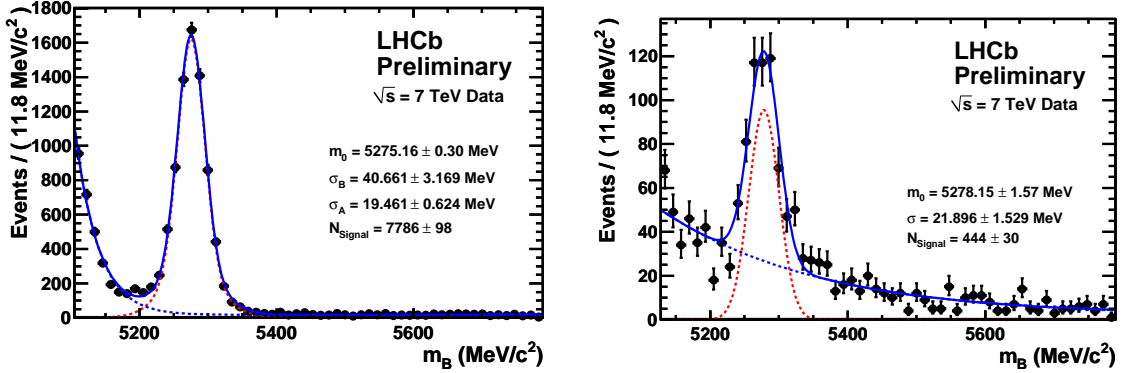


Figure 7: LHCb $B \rightarrow D(K\pi)h$ decays with 34 pb^{-1} . Left: using RICH to select $B \rightarrow D\pi$. Right: using RICH to select $B \rightarrow DK$. (Note that the plots cannot be interpreted in a quantitative manner without knowledge of the RICH particle identification performance.)

study of the time integrated CP-asymmetry in $D^0 \rightarrow \pi\pi$ events was made public [44]. When interpreted as a search for direct CP-violation, this measurement has around twice the precision of those performed at BABAR and Belle.

5 Conclusions

For several years at least (and with the exception of BES-III), B and D physics will be pursued solely at hadron colliders. Although the $\Upsilon(4S)$ is a wonderful environment for flavour studies, the power and potential of the data still to be exploited at CDF and D0, and those now accumulating at LHCb, is difficult to overstate. The B_s^0 meson and b -baryon sectors will start to reveal their secrets, and very high statistics studies will continue with B^0 , B^+ and D mesons. It is certainly no dark age for flavour studies – here comes the sun!

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